FLOODING CRITERION FOR EVAPORATIVE COOLING ON HORIZONTAL SEMI INFINITE SOLIDS

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ABSTRACT

The evaporative cooling of a sparse spray impacting on a hot solid is investigated to determine the limiting condition associated with the liquid flooding of the solid surface. The flooding condition is identified when the evaporation rate is insufficient to remove the amount of water being deposited on the surface. The flooding criteria is derived as a function of the initial single droplet volume prior to deposition, the Evaporation-Recovery Cycle (ERC) and the area of influence, which describes the region of the solid surface associated with a single droplet cooling effect. These last two quantities, the ERC and the area of influence, are evaluated by integrating previously obtained theoretical and experimental information with selected experimental data obtained in this study. The flooding criteria, while semi-empirical in its derivation, can be generalized to all non-porous solids under a variety of conditions. The spray is sparse and the water droplets are considered of uniform size. Extension to a spray with non-uniform droplet distribution is not considered here.

NOMENCLATURE

A	area influenced by the evaporative cooling of a single droplet, m^2
c_S	specific heat of the solid, J/kg K
erf	error function
F_R	recovery factor: $= \tau_{ERC}/\tau$
J_0, J_1	Bessel's functions
JA	Jakob number: $= c_S (T_0 - T)/\Lambda$
k_S	thermal conductivity of the solid, W/m K
r	radial coordinate, m
R	radius of the solid-liquid interface, m
T	solid surface temperature, K
T_0	initial solid surface temperature, K
U_{max}	water spray volumetric flux at the onset of flooding, m^3/m^2s
V	droplet volume at deposition, m^3

<u>Greek</u>

α_S	thermal diffusivity of the solid, m^2/s
β	shape parameter: $= R / (3\ V/4\ \pi)^{1/3}$
δ	non-dimensional thermal penetration depth: $= (\alpha_S\ \tau)^{1/2}/R$
η	non-dimensional radial coordinate: $= r/R$
η_i	non-dimensional radius of influence: $= 0.6\ \eta$ where η is obtained from the closed form solution (Equation 5) setting $\phi = 10^{-3}$
θ	non-dimensional solid surface temperature: Equation 1
λ	dummy variable of integration
Λ	latent heat of vaporization, J/kg
ρ_L	density of the water, kg/m^3
ρ_S	density of the solid, kg/m^3
τ	single droplet evaporation time, s
τ_{ERC}	single droplet Evaporation-Recovery Cycle (ERC), s
ϕ	parameter defining the radius of influence: Equation 4

INTRODUCTION

The cooling effect of water sprays on solid surfaces has been the subject of numerous investigations. Toda (1972) and Bonacina et al. (1979) provided some early insight in the phenomena. Rizza (1981) and Tio & Sadhal (1992) modeled the spray cooling phenomena. Grissom & Wierum (1981) defined the range of conditions for evaporative cooling. Several investigators focussed their attention on the behavior of single droplets both experimentally and theoretically. Pedersen (1970), Makino & Michiyoshi (1987), Zhang & Wang (1982) and Chandra & Avedisian (1991) made great strides in the understanding of the phenomena while Seki et al. (1972), diMarzo & Evans (1989), diMarzo et al. (1993), Tartarini & diMarzo (1994) and White et al. (1994) provided models for single droplet evaporation for a broad range of conditions.

This work focusses on the issue outlined by Grissom & Wierum (1981): the maximum water flux that can be evaporated on a hot surface defines the limit between evaporative cooling and flooding of the solid surface. The criterion for the evaluation of the maximum water flux presented here is grounded in the single droplet models previously derived. Therefore, a brief background is provided to summarize these earlier findings.

BACKGROUND

Extensive experimental and theoretical investigations resulted in the formulation of a coupled model of the interaction of a water droplet deposited on a solid surface. The reader should consult diMarzo et al. (1993) and White et al. (1994) for the details. The coupled model is based on the simultaneous solution of the liquid and solid domains with mixed numerical techniques which included a boundary element method for the treatment of the solid domain. The water droplet is subjected to an energy and mass balance boundary condition at its exposed surface. The heat input can be by conduction from below the solid or by radiation from above the solid surface. In this second case, the droplet evaporation is caused by direct radiant heat input as well as by conduction at the liquid-solid interface. Note that the coupled model is limited to evaporative conditions. This means that the vapor is generated at the water droplet exposed surface and nucleate boiling at the solid surface is suppressed.

The solution obtained with the coupled model provides an accurate representation of the physical phenomena and has been validated against numerous data sets. However, it is not in a simple form amenable to the derivation of a flooding criterion. A closed-form solution for a similar problem is used as a fitting routine which well represents the model results. Note that this solution is only a fitting routine since the details of the coupled model results are not captured in full. The closed-form solution is obtained by Carslaw & Jaeger (1959) for the case of a constant heat flux applied over a circular region of a semi infinite solid surface. The temperature distribution over the solid surface is given, in non-dimensional form, as:

$$\theta = JA \left(\frac{\rho_S}{\rho_L}\right) \delta^2 \beta^3 = \frac{4}{3} \int_0^\infty J_0(\lambda\,\eta)\, J_1(\lambda)\, erf(\lambda\,\delta)\, \frac{d\lambda}{\lambda} \qquad (1,2)$$

In this expression, the parameter δ represents a non-dimensional thermal penetration depth normalized with respect to the radius of the solid-liquid interface. The parameter β, introduced by Bonacina (1979), characterizes the shape of a droplet deposited on a solid. This parameter, which is referred to as the shape parameter, is the ratio of the radius of the solid-liquid interface over the radius of an equivalent-volume-droplet in spherical configuration.

FLOODING CRITERION

The flooding criterion is based on a single droplet cooling effect. The maximum heat flux, that can be removed without causing flooding, is achieved when a droplet impacts the same site with a frequency that enables the surface temperature to cycle indefinitely. This implies that the initial solid surface temperature is recovered after the complete evaporation of a given droplet prior to the deposition of the subsequent one. The area of the surface involved in this periodical heat transfer process is defined as the area of influence or the area influenced by the evaporative process. The flooding criterion can be expressed in terms of the maximum volumetric water flux, U_{max}. The heat associated with the vaporization of a droplet of volume, V, is applied uniformly to the area influenced by the droplet, A, over the total droplet Evaporation-Recovery Cycle (ERC), τ_{ERC}. Therefore, the flooding criterion can be written as:

$$U_{max} = \frac{V}{A\,\tau_{ERC}} \qquad (3)$$

In order to derive the flooding criterion, one must evaluate the area of influence, A, and the evaporation-recovery cycle, τ_{ERC}. This is accomplished in the following.

Evaporation-Recovery Cycle

The ERC is determined experimentally by depositing a sequence of droplets, on the same point of the solid surface, while heating the solid by conduction from below. For a given heat flux, one can determine the maximum frequency of deposition which corresponds to the onset of flooding. These experiments are also corroborated by computations performed with the coupled model (White et al. 1994; diMarzo et al. 1993) and by experimental observations of the infrared thermography of the surface (Klassen et al. 1992; diMarzo et al. 1992). From all these sources it has been determined that the recovery time, for a broad range of conditions, lasts 30 percent of the evaporation time. Figure 1 provides a typical comparison of the ERC evaluated by multiplying the evaporation time, τ, by the recovery factor, F_R, which is set to 1.3. These results indicate that this approach provides a reasonable estimate for τ_{ERC} to be used in Equation 3.

Area of Influence

The determination of the area influenced by the single droplet evaporative transient is a more complex endeavor. The first step is to introduce the concept of radius of influence as the radial position beyond which the heat flux in the radial direction is less than a given percent, ϕ, of the reference heat flux associated with the droplet vaporization. This reference heat flux is the heat of vaporization of a droplet of volume V applied to the solid-liquid interface of radius R over the evaporation time τ. This definition of radius of influence can be written as:

$$-k_S \frac{\partial T}{\partial r} = \phi \frac{\rho_L V \Lambda}{\pi R^2 \tau} \qquad (4)$$

In terms of the same non-dimensional variables used in Equations 1 and 2, Equation 4 becomes (see diMarzo et al. 1993):

$$\int_0^\infty J_1(\lambda\,\eta)\, J_1(\lambda)\, erf(\lambda\,\delta)\, d\lambda = \phi \qquad (5)$$

This result defines a functional relationship between the non-dimensional radial position η and the parameter ϕ for given values of the non-dimensional penetration depth δ.

In order to evaluate the radius of influence (i.e. the area of influence), two steps are needed:

a) the relationship between the closed-form and the coupled model results must be found; and
b) the value of ϕ must be estimated.

Figure 2 provides the comparison between the above expression (Equation 5) and the coupled model results, for a broad range of conditions and for ϕ ranging over several orders of magnitude. As it can be seen, it is reasonable to modify the results by considering sixty percent of the value of η obtained with the closed-form solution. Note that materials with low thermal diffusivity (i. e. glass, quartz, etc.) exhibit low values of η (up to 4 in the figure). In this case, a smaller multiplier could be used (i. e. 50%) since the points are above the 45° line. For high thermal diffusivity materials (i. e. steel, aluminum), large values of η are observed. In this case the opposite is observed and a larger multiplier (i. e. 70%) could be used since the points are below the 45° line. In summary, the selection proposed here is a reasonable compromise for all possible solids within the 15% accuracy, identified in the figure by the dashed lines.

The next step is the evaluation of the parameter ϕ. This step is carried out experimentally by setting two parallel streams of droplets at near flooding conditions. The first stream impacts a fixed point while the other stream impacts locations which are made progressively closer to the fixed location. As the distance between these two sites is decreased, the onset of flooding is observed. By determining the minimum distance for which the two streams of droplets are independent of each other, one obtains the radius of influence. Note that this experimental determination of radius of influence is not ideal since a one-dimensional measurement (i. e. along a single radius) is substituted for a two-dimensional phenomenon. In reality, a single droplet is surrounded by other randomly distributed evaporating droplets. This observation is most important and limits the significance of the data to the determination of the order of magnitude for the parameter ϕ and not to its specific numerical value.

In this spirit, Figure 3 illustrates data obtained on Macor (a glass-like material). Note the behavior in the low range near the origin where significant discrepancies in the trend between the closed-form solution and the data indicate that the two-dimensional effects are indeed important. Due to this realization, data at higher values of δ (i. e. for high thermal conductivity materials) are not obtained because of the uncertainty associated with the two-dimensional effect. For this study the value of
$\phi = 10^{-3}$ is selected. This selection can be regarded as the fitting of a single semi-empirical parameter for the flooding criterion formulation.

Figure 4 provides the values of the radius of influence for a variety of conditions using Equation 5 with ϕ set equal to 10^{-3} and with η_i equal to sixty percent of the value of η obtained from the equation. To further simplify the evaluation of the radius of influence, these results can be represented with an exponential fit given as:

$$\eta_i = 11\left(1 - e^{-\delta/6}\right) \tag{6}$$

This expression, which is applicable to most solid materials (e. g. glass, quartz, steel, aluminum), is used to evaluate the area of influence in Equation 3. Recall that the radius of the solid-liquid interfacial region can be expressed as a function of the shape parameter β to yield the following result:

$$A = \pi\left(\beta\,\eta_i\right)^2\left(\frac{3V}{4\pi}\right)^{2/3} \tag{7}$$

This formulation can now be substituted in Equation 3.

Criterion Evaluation

The final form of the criterion, with the substitution of Equation 7 into Equation 3 and with the introduction of the recovery factor $F_R = 1.3$, yields:

$$U_{max} = \frac{5.3 \times 10^{-3}\, V^{1/3}}{\beta^2\,\tau\left(1 - e^{-0.27\frac{\sqrt{\alpha_s \tau}}{\beta V^{1/3}}}\right)} \tag{8}$$

This criterion is general in that the closed-form solution is fitted to the coupled model which has been validated for a broad range of material thermal properties. Further, the criterion is readily extended to the case of radiant heat input from above since it has been shown that the closed-form solution provides a good representation of the droplet evaporative transient also for that case (White et al. 1994). Finally, note that, in order to determine U_{max}, it is necessary to know the following:

1) the shape parameter ,β;
2) the droplet volume, V;
3) the evaporation time, τ;
4) the solid thermal diffusivity, α_S.

These quantities are known (i. e. α_S and V) or can be evaluated with a simple single droplet experiment (i. e. β and τ). It is important to realize that this flooding criterion is derived for a spray with single-sized-droplet distribution. The extension to the case of a spray with a drop size distribution is not considered here.

Figure 5 compares the flooding criterion with the data available from experiments reported by Dawson and di Marzo (1993). These experiments are for spray cooling of a surface heated by radiation from above. As it can be seen, the criterion provides an excellent representation of the experimental conditions. The uncertainties associated with the criterion are due to the semi-empirical determination of the parameter ϕ . The uncertainty band is identified by the two dashed lines in the figure. Consider also that the experimental determination of the onset of flooding conditions is not clearly defined since it requires the establishment of a quasi-steady state. This condition is not easily met, during spray cooling with a sparse spray, because local conditions vary greatly depending on the specific droplet deposition pattern. Therefore, the average surface temperature of a portion of the solid will vary significantly about its average. These considerations of the inherent fluctuating behavior of the surface temperature support the order-of-magnitude approach for the selection of the parameter ϕ. In the figure, the onset of nucleate boiling is shown at 163° C. This is the case for water droplets deposited on Macor. The power supply in the experimental apparatus is limiting the upper bound of the volumetric flux for the data set at 163°C.

CONCLUSIONS

A criterion for the determination of the onset of a flooding condition of a hot surface subjected to a water sparse spray is presented. The criterion is formulated on the basis of a single droplet vaporization process via the introduction of two parameters: the ERC and the area of influence. These two parameters are evaluated from experimental and theoretical considerations for single droplets.

The final form of the criterion is based on the determination of the parameter ϕ which represents the ratio of the limiting radial heat flux in the direction of an evaporating droplet and the reference heat flux associated with the whole droplet evaporation process. A simple experiment is used to inform the selection of the parameter ϕ which is set at 0.1 percent of the reference value (i. e. $\phi = 10^{-3}$). With this selection, a closed-form solution is used to fit the data of a previously developed coupled model for the single droplet vaporization. The overall results are well represented by an exponential curve fit which enables the derivation of the flooding criterion in its final form.

The criterion is based on four parameters which are readily available or that can be determined from single droplet vaporization experiments. Experimental data on sparse sprays confirms that the criterion is able to bound the region where evaporative cooling can be achieved without flooding the solid surface.

FIGURES

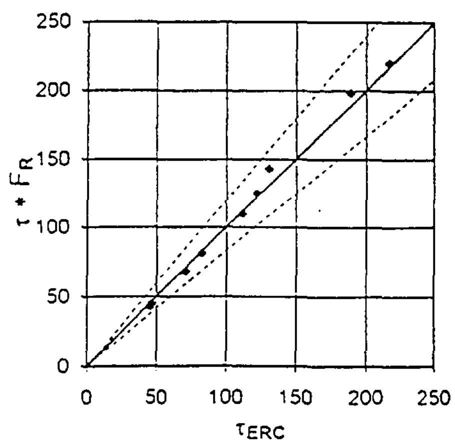

Figure 1. Comparison of τ with τ_{REC} when $F_R = 1.3$

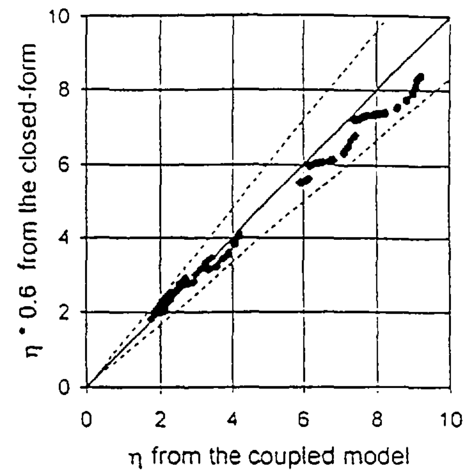

Figure 2. Comparison of η from the Coupled Model With Sixty Percent of η Obtained From the Closed-Form Solution

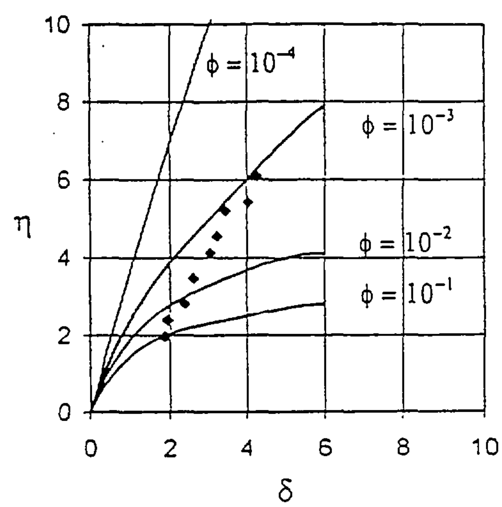

Figure 3. Comparison of the Data with the Trends Obtained with the Closed-Form Solution

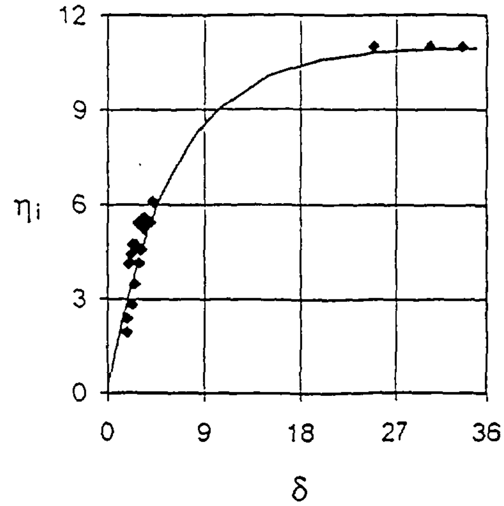

Figure 4. Comparison of the Results of the Closed-Form Solution with the Exponential Fit

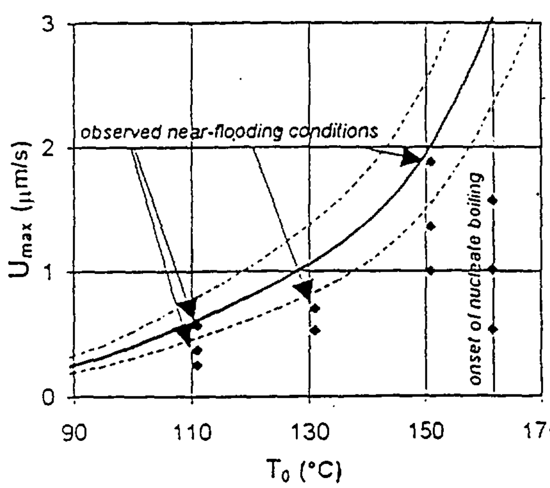

Figure 5. Comparison of the Criterion with the Data From Sparse Water Sprays (Dawson and di Marzo, 1993)

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